IOP Conf. Series: Materials Science and Engineering 139 (2016) 012008 doi:10.1088/1757-899X/139/1/012008

Tensile failure of hybrid composites: measuring, predicting and understanding

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Abstract. Fibre-hybrid composites are attracting an ever-increasing interest from academia and industry. It is therefore vital to develop a solid understanding of their basic mechanical properties. Measuring and predicting the tensile failure of hybrid composites however remains a challenging task. This paper describes how failure develops in unidirectional (UD) hybrid composites, and how this can be predicted using fibre break models. It also provides recommendations for experimental measurements of the hybrid effect, which is a synergetic increase of the failure strain of low elongation fibres when hybridised with higher elongation fibres. Finally, limitations of our understanding of the tensile failure of hybrid composites are discussed and recommendations for future research are proposed.

1. Introduction

Fibre-reinforced polymer composites are composed of fibres in a polymeric matrix. The fibres impart stiffness and strength, whereas the matrix provides structural integrity. The low density of the matrix and fibres combined with excellent mechanical properties makes composites a preferred choice in many lightweight applications. The two most common reinforcement fibres are carbon and glass. Carbon fibres are typically used in applications where the highest performance is needed, such as sports and aerospace industries. Glass fibres, which are 5-10 times cheaper than carbon fibres, are more common in applications where cost is the main driver. Cost is however not straightforward to define for a subcomponent, and should also be evaluated on the global level. The increased use of carbon fibre composites in airplanes is a good illustration of this point. In recent airplanes like the Boeing 787 Dreamliner and Airbus A350, carbon fibre composites have replaced a large part of the advanced metal alloys, even though such alloys are cheaper. Nevertheless, carbon fibre composites lead to lighter parts, which reduce fuel consumption and eventually lead to cost savings over the lifetime of the airplane.

One of the greatest benefits of fibre-reinforced composites over other material families is the potential they offer for design optimisation. Being able to choose the fibre type, matrix type, the layup and the preform gives designers a myriad of options. Not being restricted to a single fibre type expands this design envelope even further. The development of fibre-hybrid composites, like carbon/glass hybrids, is therefore a logical evolution towards even more design freedom and hence more possibility for optimisation and cost reduction. Recently, researchers are also starting to explore other types of fibres, such as carbon/polypropylene [1], carbon/polyamide [2] or glass/natural fibres [3]. This further expands the potential design freedom that can be achieved through fibre-hybridisation.

Since carbon and glass fibres are the dominant reinforcement fibres, carbon/glass hybrids have also been the dominant hybrid combination. Carbon/glass hybrids were initially developed to reduce the cost of carbon fibre components in the sixties [4]. This triggered a large body of research in the seventies and the eighties [5-12] to explore their mechanical properties. The typical stress-strain diagram of a hybrid composite (see Figure 1) shows two distinct peaks, which are associated with failure of the low (carbon) and high elongation (glass) fibres respectively. The transition between these two peaks can be sharp as in Figure 1, or can consist of a plateau [13].

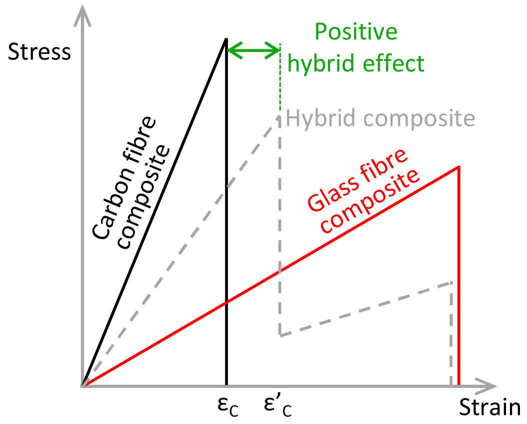

Figure 1: Schematic stress-strain diagram of a hybrid composite and its two reference composites. The hybrid shows two peaks, which are linked to failure of the carbon and glass fibre composite respectively.

In 1972, Hayashi [14] reported a remarkable effect, which later turned out to be the subject of intense scientific discussions [5]. By sandwiching a carbon fibre layer in between glass fibre layers, Hayashi improved the tensile failure strain of the carbon fibre layer by 40%. In terms of Figure 1, this means that the first peak shifted from ε_C to ε'_C, which is an increase of 40%. The term “hybrid effect” was coined to describe this synergetic effect. It is defined as the relative increase of the failure strain of the carbon fibre composite/layer in a hybrid composite relative to the failure strain in an all-carbon fibre composite. With reference to Figure 1, the hybrid effect can be calculated as:

$$Hybrid\ \ effect = \frac{\varepsilon'_C - \varepsilon_C}{\varepsilon_C} \tag{1}$$

The origin of the hybrid effect was initially unclear, which greatly contributed to the initial controversy. Later, three hypotheses were coined: (1) thermal residual stresses [8,9], (2) changes in the damage development leading to final failure [8,15], and (3) dynamic stress concentrations [16]. Many authors have reported on the hybrid effect, and a collection of the experimental data is presented in Figure 2.

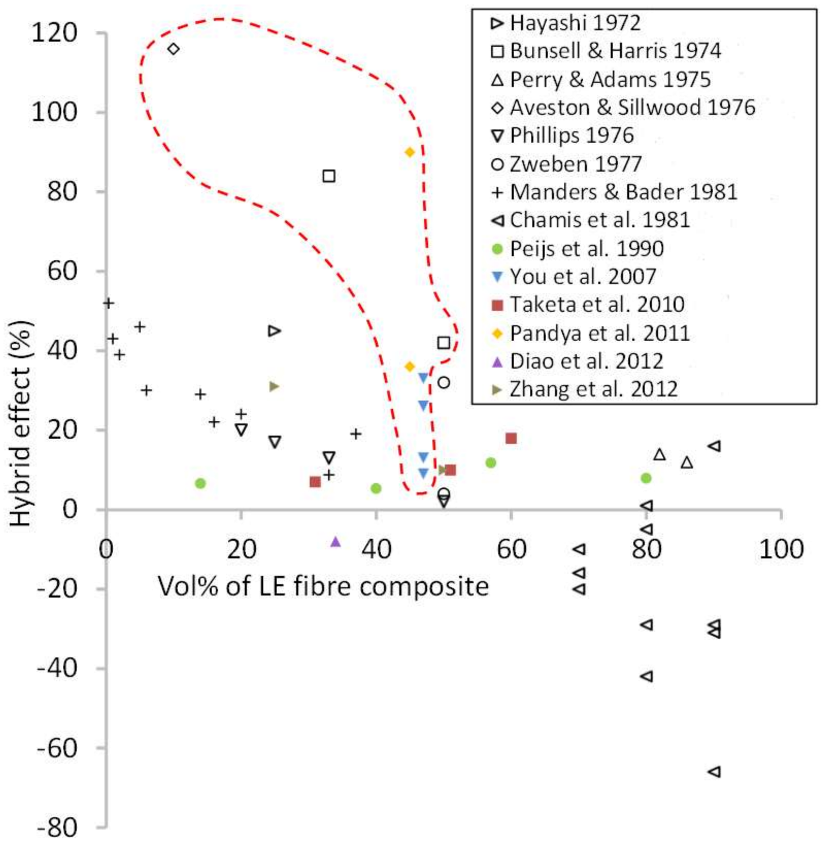

Figure 2: Overview of experimentally measured hybrid effects in carbon fibre-reinforced hybrids, with LE indicating the low elongation fibre, i.e. carbon fibre. Data from before 1987 are in black, whereas more recent data are in colour. The red dashed line encircles data points that are doubtful. (reprinted from Swolfs et al. [17] with permission from Elsevier).

Until a few years ago, there was no model available to quantitatively compare the experimental data against. These models were all based on 1D packings [8,18,19], which implies a single row fibres. The failure development in such simplified packings is significantly different from that in 2D packings. 1D packings also fail to properly capture fibre dispersion, which is well recognised to have a drastic influence on the hybrid effect [17]. Based on such models, it was therefore difficult to judge how realistic the data in Figure 2 is. Recent modelling evidence however, revealed that the hybrid effect at its best is up to 20% [20,21]. Such high values could be achieved for very thin carbon fibre layers or for very well-dispersed hybrids only. The data in Figure 2 seem to reveal an upwards trend towards 40% with decreasing carbon fibre content. This is significantly higher than the highest modelling predictions, and seems unrealistically high in light of the rather low degrees of dispersion that were achieved.

A part of the discrepancies in Figure 2 can be explained by the inherent difficulties in measuring the hybrid effect. The hybrid effect is normally measured by comparing the failure strain of a carbon fibre composite to that of a hybrid composite, both of which contain only 0° fibres. Tensile tests on fully unidirectional (UD) carbon fibre composites are however challenging to perform for three reasons. Firstly, the grips induce stress concentrations [22,23], which increases the probability of failure at the grips. Secondly, the grips limit the Poisson contraction within the grips, while such contraction is unconstrained outside of the grips. This creates a tendency for premature onset of splitting just outside of the grips [24]. Finally, the high stiffness and strength of UD carbon fibre composites lead to a very high energy release when they fail. This creates additional damage and failure, thereby disguising the location of the initial failure [24]. It is therefore difficult to establish whether failure started within the gauge length or near the grips. These three problems can lead to underestimations of the reference carbon fibre failure strain. Additionally, hybridisation with glass fibre will tend to reduce the severity of the first and third problem. All of this combined will tend to lead to overestimations of the hybrid effect.

This paper will investigate the tensile failure of hybrid composites, and attempt to discern best practices for measuring and predicting it. This will be necessary to advance our understanding of the tensile failure of hybrid composites.

2. Predicting the hybrid effect for initial failure strain

2.1. Failure development

The failure of unidirectional fibre-reinforced composites is controlled by fibre breaks. Since fibre strength follows a Weibull distribution, some fibres will have a relatively low strength. These fibres fail first, and locally lose their load transfer capability. The length over which they lose this capability, is called the ineffective length. Over this length, the broken fibres will shed their load to the nearby fibres, which causes stress concentrations [25]. The stress concentrations will increase the failure probability of the nearby fibres, thereby causing a tendency to create clusters of fibre breaks. These clusters cause even larger stress concentrations [26]. Eventually, a critical cluster will develop that will propagate rapidly and cause the entire composite to fail.

The failure development in hybrid composites essentially follows the same steps, but with a few additional complications. At a given strain, the high elongation fibres are less likely to fail than the low elongation fibres. This has two consequences. Firstly, this reduced failure probability of the high elongation fibres hinders the development of clusters of fibre breaks, as the high elongation fibres limit the number of pathways for the cluster to grow into. Secondly, in a given volume of composite material, there are now less low elongation fibres. This reduces the probability of finding a collection of relatively weak fibres that will cause the formation of a cluster, and eventually the critical cluster. These aspects will contribute to increasing the strain at which the low elongation fibres or plies fail.

A key implication of this failure process is that correctly capturing the microstructure is essential to accurate predictions of the failure development [18]. Swolfs et al. [21] have recently revealed how important this could be (see Figure 3). Alternating hybrid carbon/glass microstructures with different layer thicknesses were modelled, and the hybrid effect was found to increase significantly with decreasing layer thickness. Having layers of a single fibre thick led to a hybrid effect of 16%, which was larger than that of a randomly dispersed configuration. For layers that were 8 fibres thick, the hybrid effect reduced to about 2%. It should be noted though that most commercial plies are much thicker.

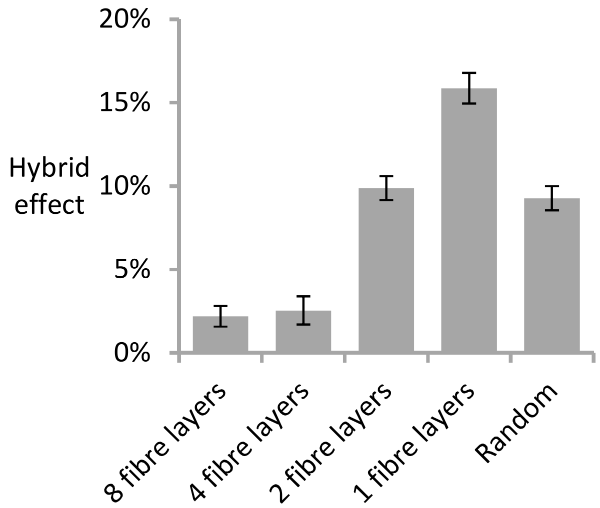

Figure 3: The hybrid effect as a function of the microstructure (reprinted from Swolfs et al. [21] with permission from Elsevier).

2.2. State-of-the-art models

The development of strength models for UD hybrid composites started with Zweben's model in 1977 [8]. Zweben's model was based on a 1D packing, which is basically a single row of parallel fibres. Zweben's hybrid packing was a single row of alternating carbon and glass fibres. Such a model hence does not capture the microstructure of a real hybrid composite. Nevertheless, this model was a breakthrough, as it was the first one proving the hypothesis that adding high elongation fibres delays the development of fibre breaks. Given the initial confusion and discussions on the hybrid effect in the early seventies [5], this model was a landmark for future model developments.

The reader is referred to the original work [8] for more details, but several key conclusions can be drawn from his work:

- Small Weibull moduli, which correspond to a large strength scatter, should lead to large hybrid effects.
- The ineffective length and stress concentrations have a minor influence on the hybrid effect.
- The largest hybrid effects are achieved if the two fibre types have a large difference in their average failure strains.

Conclusion #1 confirms that the hybrid effect is essentially a result of the scatter in the fibre strength of the low elongation fibre. This is well captured in the statement of Manders [27]: "*the hybrid effect arises from a failure to realise the full potential strength of the fibres in all-carbon fibre composites, rather than from an enhancement of their strength in the hybrids*". Conclusions #2 and #3 require further validation with more advanced models, as the assumptions and simplified geometry of Zweben's model may have tainted these conclusions.

The next step in the model development for hybrid composites was achieved by Fukuda [28] in 1984. He addressed some of the shortcomings of Zweben's model, but still used the same basic geometry. Fukuda's model revealed that the failure strain of the high elongation fibre does not influence the hybrid effect. This invalidates conclusion #3 from Zweben's model. While Zweben's model perhaps exaggerated the influence of the high elongation failure strain, Fukuda's model underestimated it. More refined models with realistic microstructures are needed to assess the importance of the high elongation failure strain.

After the models of Zweben and Fukuda however, the progress in this area was relatively slow. There was some progress in later years [18,29], but these were still limited for relatively simple microstructures or packings. Models for non-hybrid composites were developing at a much faster rate. Only in recent years, the models for hybrid composites are catching up. Swolfs et al. [30] developed a model based on global load sharing, which was further developed by Rajan and Curtin [31]. While global load sharing theory inherently ignores the local microstructure, this approach does capture several of the basic phenomena:

- The hybrid effect increases when more high elongation fibres are added, which confirms the overall trend in Figure 2.
- A small Weibull modulus for the low elongation fibre leads to a larger hybrid effect, which confirmed conclusion #1 from Zweben's model.
- A small Weibull modulus for the high elongation fibre leads to a smaller hybrid effect.
- Larger differences between the failure strains of both fibre types increase the hybrid effect, which confirms Zweben's conclusion #3. This effect is however relatively small, and when a certain ratio of both failure strains has been exceeded, no further benefit is obtained.

More advanced models were developed simultaneously by Swolfs et al. [20,21]. The first model was based on very local load sharing in a hexagonal packing [21]. This approach simplified several aspects, such as:

- Assuming both fibre types have the same radius.
- Assuming only the six nearest neighbours carry the stress concentrations.
- Using hexagonal packings instead of the more realistic random packings.
- Using a linear stress recovery in the broken fibre instead of the actual stress recovery profile.

A second model improved all these aspects by using a random fibre packing, which also allowed to include fibres with different radiuses [20].

Figure 3 revealed the key conclusion from the first model: the microstructure is essential in accurately predicting the hybrid effect. Having alternating layers of a single fibre thick led to a hybrid effect of 16%, which was larger than the 10% achieved for a random dispersion. While this is a reasonably large hybrid effect, it is still significantly lower than the 40% found by Hayashi. Compared to the other literature data in Figure 2, this may seem realistic at first. However, most of this data was obtained for much poorer dispersion. In some cases, the layer thicknesses were several 100 μm, in which case, the model predictions would predict a hybrid effect close to 0%. There is hence a significant discrepancy between modelling predictions and the experimental measurements. The question therefore is: is this discrepancy caused by inaccurate models or by inaccurate measurements? Let us first turn to potential issues with the modelling predictions.

As with any model, models for hybrid composites require several simplifications. Additionally, a model is only as reliable as its input data. There are several issues with the input data that have been identified. The most prominent issue is the reliability of the Weibull distribution for fibre strength [32]. Accurately determining this distribution is challenging from an experimental point of view, as it requires hundreds of accurate tests and a time-consuming preparation. As explained before, the Weibull distribution for the high elongation fibre is not crucial for the hybrid effect predictions. The Weibull distribution for the low elongation fibre however has an important effect on the predictions. While the literature on this specific topic is not exhaustive, there are strong indications that a small Weibull modulus for the low elongation fibre will increase the hybrid effect (see Figure 4). This also makes sense in light of Manders' quote: a small Weibull modulus implies that the all-carbon fibre composites is far away from reaching the potential strength of the fibres. Adding a high elongation fibre allows the hybrid composite to get closer to this potential strength.

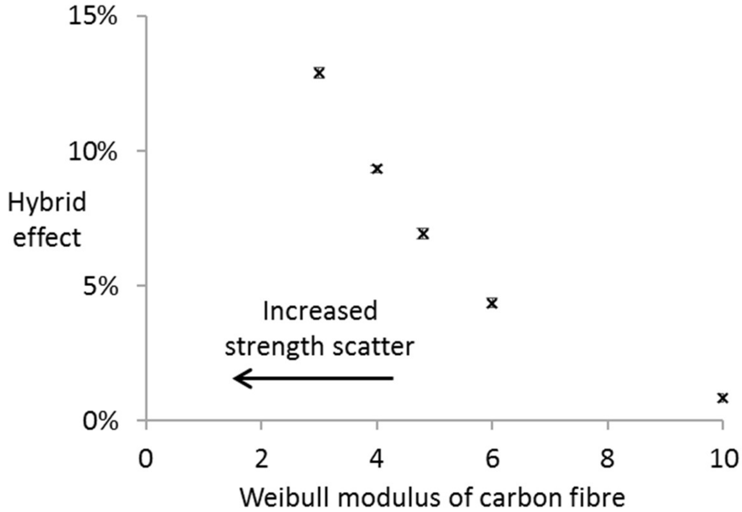

Figure 4: The hybrid effect decreases strongly with increasing Weibull modulus of the low elongation fibre (reprinted from Swolfs et al. [20] with permission from Elsevier).

The next question is how the results in Figure 4 could help to explain the large discrepancy between modelling predictions and experimental results. Close inspection of Figure 2 reveals that the majority of the data points with a large hybrid effect were obtained in the seventies and the eighties. Carbon fibre production in those days was not as well developed as it is at the moment. It is not unreasonable to assume that the lower quality of the carbon fibres also resulted in a large fibre strength scatter and hence a lower Weibull modulus. While this could bring the modelling predictions closer to the experimental values in Figure 2, the influence seems too small to explain the complete discrepancy.

2.3. Experimental validation

As any strength model for UD composites has inherent assumptions, the discrepancy could also be explained by the fact that models for UD hybrid composites are not capturing all relevant mechanisms. Experimental validation is therefore a crucial step to confirm the validity of strength models. KU Leuven and the University of Bristol have recently teamed up for such an experimental validation. Thin carbon fibre plies of 29 µm were sandwiched in between thicker glass plies. Every carbon fibre plies contained an average of just three fibres through the thickness. By changing the number of carbon fibre plies in the middle, different values for the hybrid effect could be obtained, as predicted by Figure 3. If sufficient carbon fibre plies are used, the hybrid effect should revert to zero, which means that this failure strain can be used as the reference failure strain for calculating the hybrid effect. Changing the number of carbon fibre plies from 1 to 4 was enough for achieving this objective.

Figure 5 presents the decrease in the hybrid effect with increasing number of carbon fibre plies. The hybrid effect decreases to 0% when 3-4 plies have been used, which means that the hybrid effect is absent for layer thicknesses above 100 µm. For layer thicknesses of 25-30 µm however, hybrid effects of up to 12% (for the model) and 18% (for the experiments) could be achieved. While the model parameters were fitted to achieve the correct reference failure strain (see dashed line in Figure 5), the predictions for the hybrid effect capture the correct trend. This is an encouraging result, as it demonstrates that the model captures the most important micromechanical phenomena.

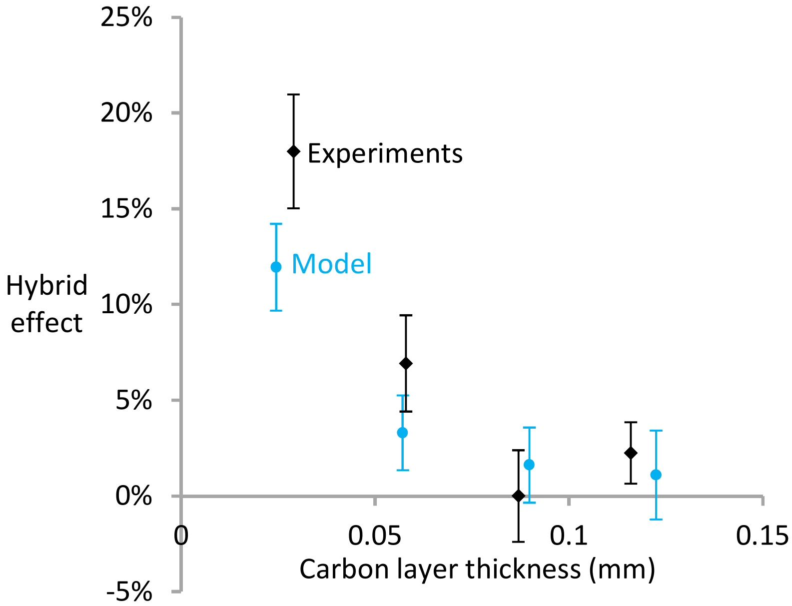

Figure 5: The model predicted the experimentally measured failure strain of hybrid composites well. The presence of thermal residual stresses were taken into account. (data based on Wisnom et al. [33])

What was so unique about this set of experiments that it matched well with the modelling predictions? The main improvement lies in the way that the reference failure strain was determined. This value is typically obtained by measuring the failure strain of the carbon fibre plies in an all-carbon fibre composite. That approach however is flawed, as testing non-hybrid UD composites nearly always leads to underestimations of the strength and failure strain. The introduction revealed three main issues in tensile testing of UD composites: (1) stress concentrations at the grips, (2) Poisson contractions near the grips, and (3) difficulties in establishing the origin of the failure. Stress concentrations at the grips have been widely discussed in literature [22,23]. They can be somewhat reduced by the use of suitable end tabs, but completely avoiding them seems to be impossible. For UD composites, an additional problem arises due to the Poisson contractions near the grips. Within the grips, the Poisson contractions are prevented, while outside the grips the sample can freely contract. This creates a tendency to initiate splitting near the end tabs. A final problem is that UD composites release a large amount of strain energy when they fracture. This rapidly creates secondary damage, thereby obscuring the initial failure location. Without a clear determination of the initiation location, it is impossible to determine whether failure started sufficiently far from the grips to qualify as a good test.

All three issues mentioned above can be resolved by placing a relatively thick layer of carbon fibre plies in between glass fibre plies:

- The glass fibre plies shield the carbon fibre plies from the stress concentrations at the grips.
- The glass fibre plies have a lower tendency for splitting, and they will also help to prevent splitting of the carbon fibre plies if their volume fraction is sufficiently high.
- By limiting the amount of carbon fibre in the hybrid composite, the amount of energy released upon failure is significantly reduced and the glass fibre continues to carry load. This allows an easy determination of the initiation location.

One additional issue that can arise is the occurrence of thermal stresses. As glass fibres have a larger coefficient of thermal expansion than carbon fibres, the proposed hybrid layup results in compressive stresses on the carbon fibre layer(s). These stresses can however be predicted and accounted for in the calculations, as was also done by Wisnom et al. [33].

Having all of this information, the literature can be re-examined. Examining the references cited in Figure 2 in more detail, it becomes clear that they did not describe how their samples failed or how failure at the grips was prevented or monitored. This makes it rather likely that the large hybrid effects they achieved, were caused by an unrealistic low value for the failure strain of their low elongation fibre composite. The proposed approach would hence be to sandwich a sufficiently thick layer of the reference material in between two layers with a higher failure strain.

3. Limitations in our understanding

Predictive models have greatly helped to advance our understanding of the tensile failure of hybrid composites. Being able to predict the hybrid effect for failure initiation was a large step forward. It is however not the end point, as there are still several open questions and areas for further improvement.

3.1. Improvements for initial failure

One of the open questions for modelling the initial failure is the importance of dynamic effects. When a fibre fails, it releases strain energy and springs back, thereby causing dynamic stress concentrations on the nearby fibres. The existence of dynamic stress concentrations is undisputed in the literature, but its importance remains unclear. While several authors have indicated that these dynamic effects can be up to 50% larger than the static ones [34-36], it remains unclear how large the influence on the failure would be. No one has included dynamic stress concentrations in a strength model yet, and the understanding for hybrid composites is even more limited. Only one study has looked at dynamic stress concentrations for hybrid composites, and this study seemed to indicate that it could contribute to the hybrid effect [16]. This particular study was however based on a simple geometry consisting of a row a carbon fibres on top of a row of glass fibres. It also limited itself to stress concentrations, and did not include them in a strength model. It hence remains unknown how large the influence of dynamics on the hybrid effect is.

There are also a number of open questions with respect to modelling the strength of unidirectional composites in general. The main issue is linked to measuring the Weibull distribution for fibre strength [32]. These problems are however not linked to hybrid composites specifically, and are outside of the scope here.

3.2. Improvements for final failure

The models that can accurately capture the initial failure do not yet capture the final failure. Some models do capture the entire stress-strain diagram, but they do this by ignoring individual fibre breaks [37,38] and/or the local microstructure [30,31]. The accuracy in predicting how the final failure strain shifts by hybridisation is therefore limited. In general, it would be expected the final failure strain is slightly reduced by the presence of the low elongation fibres (see Figure 1). The fibre breaks in the low elongation fibres trigger more fibre breaks in the high elongation fibres than in the reference composite with only high elongation fibres. This should in principle lead to earlier failure of the high elongation fibres. Furthermore, the thermal residual stress that contribute to delaying the initial failure should lead to an earlier onset of final failure. In a carbon/glass hybrid, the thermal residual stresses put the carbon fibres in compression, but they put the glass fibres in tension. These tensile stresses in the glass fibres will be added on top the externally applied stresses, which will lead to an earlier onset of final failure.

3.3. Improvements for the transition between initial and final failure

In recent years, there has been significant progress in tuning the transition the between initial and final failure. This is mainly driven by the interest in achieving pseudo-ductility. Jalalvand et al. [37,38] for example has developed modelling approaches to predict how different layups lead to different transitions between the initial and final failure. A plateau region can be achieved if a suitable layer thickness and overall volume fraction of the low elongation fibre is chosen. If done correctly, the low elongation fibre layer will fragment, instead of causing an unstable delamination or immediate fracture of the high elongation fibre layers. A crucial parameter in achieving this, is the mode II interlaminar fracture toughness. This parameter determines the amount of energy required to propagate a delamination, and should be higher than the strain energy released.

The plateau region is in principle not completely horizontal, but should increase slightly. The low elongation fibre layer does not have a constant strength, but a strength varying over the length of the layer. The first fracture hence occurs in the region where the layer has the lowest strength. When this happens, the stresses and strains redistribute themselves. To cause a second failure elsewhere in the layer and start fragmentation, the stress needs to sufficiently high to cause the second weakest location to fail. This implies that the stress needs to be higher than the stress at which the first location failed. There are two inherent issues associated with this:

1. The slope of the plateau region depends on the scatter in the strength of the low elongation ply. Measuring this strength distribution is however rather difficult, as it is often affected by surface damage and other experimental variations.
2. The length of the delamination around the failure locations will determine how the stresses and strains redistribute themselves. This length is however created dynamically when the low elongation ply fails, making it challenging to predict.

Estimates for the Weibull strength distribution of plies do exist, but such estimates inevitably depend on the exact carbon fibre type and ply thickness. One powerful approach would be to use visual observation of the fragmentation in combination with models to fit the strength distribution of the plies. A similar approach could be used for the length of the delamination immediately after a fracture. This length could in principle be measured experimentally and then used in the model [39], but that would limit the usefulness of the model for blind predictions. Progress is clearly needed on both fronts to advance our capacity to predict the full tensile behaviour of hybrid composites.

Acknowledgments
YS wishes to acknowledge the European Commission for his Marie Skłodowska-Curie Individual European Fellowship at Imperial College London and FWO Flanders for his postdoctoral mandate at KU Leuven.

References

[1] Swolfs Y, Shi J, Meerten Y, Hine P, Ward I, Verpoest I and Gorbatikh L 2015 The importance of bonding in intralayer carbon fibre/self-reinforced polypropylene hybrid composites *Compos Part A: Appl Sci Manuf* **76** 299-308
[2] Hine PJ, Bonner M, Ward IM, Swolfs Y, Verpoest I and Mierzwa A 2014 Hybrid carbon fibre/nylon 12 single polymer composites *Compos Part A: Appl Sci Manuf* **65** 19-26
[3] Jawaid M and Khalil H 2011 Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review *Carbohydr Polym* **86** 1-18
[4] Phillips LN 1969 Improving racing-car bodies *Composites* **1** 50-1
[5] Phillips LN 1976 The hybrid effect - does it exist? *Composites* **7** 7-8
[6] Phillips LN 1976 On the usefulness of glass-fibre-carbon hybrids *British Plastics Federation Congress* Brighton United Kingdom
[7] Phillips MG 1981 Composition parameters for hybrid composite materials *Composites* **12** 113-6
[8] Zweben C 1977 Tensile strength of hybrid composites *J Mater Sci* **12** 1325-37
[9] Manders PW and Bader MG 1981 The strength of hybrid glass/carbon fibre Composites Part 1 Failure strain enhancement and failure mode *J Mater Sci* **16** 2233-45
[10] Short D and Summerscales J 1980 Hybrids - a review: Part 2. Physical properites *Composites* **11** 33-8
[11] Short D and Summerscales J 1979 Hybrids - a review: Part 1. Techniques, design and construction *Composites* **10** 215-21
[12] Bunsell AR and Harris B 1974 Hybrid carbon and glass fibre composites *Composites* **5** 157-64
[13] Czél G and Wisnom MR 2013 Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg *Compos Part A: Appl*

Sci Manuf **52** 23-30
[14] Hayashi T 1972 On the improvement of mechanical properties of composites by hybrid composition *Proc. 8th Intl. Reinforced Plastics Conference* 149-52
[15] Manders PW and Bader MG 1981 The strength of hybrid glass/carbon fibre composites Part 2 A statistical model *J Mater Sci* **16** 2246-56
[16] Xing J, Hsiao GC and Chou TW 1981 A dynamic explanation of the hybrid effect *J Comp Mater* **15** 443-61
[17] Swolfs Y, Gorbatikh L and Verpoest I 2014 Fibre hybridisation in polymer composites: a review *Compos Part A: Appl Sci Manuf* **67** 181-200
[18] Fukunaga H, Chou TW and Fukuda H 1989 Probabilistic strength analyses of interlaminated hybrid composites *Compos Sci Technol* **35** 331-45
[19] Fukunaga H, Chou TW and Fukuda, H 1984 Strength of intermingled hybrid composites *J Reinf Plast Comp* **3** 145-60
[20] Swolfs Y, Verpoest I and Gorbatikh L 2016 Maximising the hybrid effect in unidirectional hybrid composites *Mater Design* **93** 39-45
[21] Swolfs Y, McMeeking RM, Gorbatikh L and Verpoest I 2015 The effect of fibre dispersion on initial failure strain and cluster development in unidirectional carbon/glass hybrid composites *Compos Part A: Appl Sci Manuf* **69** 279-87
[22] De Baere I, Van Paepegem W and Degrieck J 2009 On the design of end tabs for quasi-static and fatigue testing of fibre-reinforced composites *Polym Composite* **30** 381-90
[23] Portnov GG, Kulakov VL and Arnautov AK, 2007 A refined stress-strain analysis in the load transfer zone of flat specimens of high-strength unidirectional composites in uniaxial tension - 2. Finite-element parametric analysis *Mech Compos Mater* **43** 29-40
[24] Fuwa M, Bunsell AR and Harris B 1975 Tensile failure mechanisms in carbon fibre reinforced plastics *J Mater Sci* **10** 2062-70
[25] Swolfs Y, Gorbatikh L, Romanov V, Orlova S, Lomov SV and Verpoest I 2013 Stress concentrations in an impregnated fibre bundle with random fibre packing *Compos Sci Technol* **74** 113-20
[26] Swolfs Y, Morton H, Scott AE, Gorbatikh L, Reed PAS, Sinclair I, Spearing SM, Verpoest I 2015 Synchrotron radiation computed tomography for experimental validation of a tensile strength model for unidirectional fibre-reinforced composites *Compos Part A: Appl Sci Manuf* **77** 106-13
[27] Manders PW 1979 The strength of mixed fibre composites PhD thesis University of Surrey
[28] Fukuda H 1984 An advanced theory of the strength of hybrid composites *J Mater Sci* **19** 974-82
[29] Zeng QD 1994 A statistical analysis of the tensile failure and hybrid effect of an intraply hybrid composite *Int J Fract* **68** 351-62
[30] Swolfs Y, McMeeking RM, Rajan VP, Zok FW, Verpoest I and Gorbatikh L 2015 Global load sharing model for unidirectional hybrid fibre-reinforced composites *J Mech Phys Solids* **84** 380-94
[31] Rajan VP and Curtin WA 2015 Rational design of fiber-reinforced hybrid composites: A global load sharing analysis *Compos Sci Technol* **117** 199-207
[32] Swolfs Y, Verpoest I and Gorbatikh L 2015 Issues in strength models for unidirectional fibre-reinforced composites related to Weibull distributions, fibre packings and boundary effects *Compos Sci Technol* **114** 42-9
[33] Wisnom MR, Czel G, Swolfs Y, Jalalvand M, Gorbatikh L and Verpoest I 2016 Hybrid effects in thin ply carbon/glass unidirectional laminates: accurate experimental determination and prediction *Compos Part A: Appl Sci Manuf* **88** 131-9.
[34] Hedgepeth JM 1961 Stress concentrations in filamentary structures *NASA TN* **D-882** 1-36
[35] Sakharova EN and Ovchinskii AS 1984 Influence of dynamic effects accompanying rupture of fibers and separation of fibers from the matrix on interaction between failure micromechanisms of composite materials *Mech Compos Mater* **20** 323-7

[36] Ji X, Liu XR and Chou TW 1985 Dynamic stress concentration factors in unidirectional composites *J Comp Mater* **19** 269-75

[37] Jalalvand M, Czél G and Wisnom MR 2014 Numerical modelling of the damage modes in UD thin carbon/glass hybrid laminates *Compos Sci Technol* **94** 39-47

[38] Jalalvand M, Czél G and Wisnom MR 2015 Damage analysis of pseudo-ductile thin-ply UD hybrid composites - a new analytical method *Compos Part A: Appl Sci Manuf* **69** 83-93

[39] Swolfs Y, Crauwels L, Van Breda E, Gorbatikh L, Hine P, Ward I and Verpoest I 2014 Tensile behaviour of intralayer hybrid composites of carbon fibre and self-reinforced polypropylene *Compos Part A: Appl Sci Manuf* **59** 78-84